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A PHYSIOLOGICAL EVALUATION OF ADVANCED BATTLEDRESS OVERGARMENT PROTOTYPES (ABDO)

by

W.R. Santee, W.T. Matthew
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June, 1995

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The objective was to determine if new chemical protective (CP) Advanced Battledress Overgarments (ABDO) clothing offers an advantage in reducing heat strain, relative to other CP clothing. Testing of test subjects wearing four prototype ABDO overgarments plus the issue Battledress Overgarment (BDO) was conducted in an environmental chamber. The prototypes were the 4.5 oz NYCO shell with a Von Blücher liner, the 6.0 oz NYCO shell with a Von Blücher liner, the 6.0 oz NYCO shell with 50 mil foam liner, and Gore-Tex© shell with a Von Blücher liner. The overgarments were worn over underwear in MOPP-4 configuration. Test environments were 30°C (86°F), 50% rh, with a 1.1 m·s^{-1} (2.5 mph) wind speed and 38°C (100°F), 20% rh with a 3.0 m·s^{-1} (6.5 mph) wind speed. Subjects walked on a treadmill at 3.5 mph for 100 minutes unless they reached a rectal temperature of 39°C (102.2°F), exceeded 90% of their maximum heart rate, or voluntarily ended participation. Rectal, mean skin and body temperatures, evaporative water loss (sweat), and endurance time were the dependent variables. Significant differences between garments were found for endurance times, changes in rectal and mean body temperature and the efficiency of sweating. The results of this study indicate that subjects' physiological responses were best relative to the BDO while wearing the 4.5 oz NYCO and 6 oz NYCO prototypes with the Von Blücher lining.

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EXECUTIVE SUMMARY

This study provided data on the physiological responses of volunteer subjects to heat stress while wearing prototype Advanced Battledress Overgarments (ABDO). The specific objective was to determine if new chemical protective (CP) clothing offers an advantage in reducing heat strain, relative to other CP clothing, including both standard issue and other prototypes.

Testing of volunteer subjects wearing 4 prototype Advanced Battledress Overgarments (ABDO) plus the present issue Battledress Overgarment (BDO) was conducted in an environmental chamber. The 4 prototypes were down-selected on the basis of biophysical and mathematical modeling from 6 original prototypes. The overgarments selected for testing were the 4.5 oz NYCO shell with a Von Blücher liner, the 6.0 oz NYCO shell with a Von Blücher liner, the 6.0 oz NYCO shell with 50 mil foam liner, and the Gore-Tex© shell with a Von Blücher liner. The control was the BDO with 90 mil foam liner. Subjects wore the overgarments over underwear in fully enclosed MOPP-4 configuration.

The protocol consisted of 6 consecutive days of acclimation and 10 days of regular garment testing in MOPP-4, broken into two 5-day segments. The volunteer population was divided into 2 test groups. One group tested in the morning and the second group always in the afternoon. The 2 test environments were 30°C (86°F), 50% rh, with a 1.1 $m \cdot s^{-1}$ (2.5 mph) wind speed and 38°C (100°F), 20% rh, with a 3.0 $m \cdot s^{-1}$ (6.5 mph) wind speed. On test days, volunteers entered the test chamber and stood for 20 minutes, then began walking on the level treadmills at 3.5 mph. Volunteers walked without interruption for a maximum of 100 minutes unless they reached a rectal temperature of 39°C (102.2°F), exceeded 90% of their maximum heart rate, voluntarily withdrew or were removed by the medical monitor or other staff.

Test variables were clothing (5 garments, including the control BDO) as an independent variable, and rectal, mean skin and mean body temperatures, evaporative water loss (sweat), and endurance time as dependent variables. Significant differences between garments were found for endurance times, changes in rectal and mean body temperature and the efficiency of sweating. The results of this study indicate that subjects' physiological responses were best relative to the BDO while wearing the 4.5 oz NYCO and 6 oz NYCO prototypes with the Von Blücher lining.

I. INTRODUCTION

A. PURPOSE

The purpose of the study was to evaluate the heat strain experienced by volunteer test subjects exposed to heat stress while exercising in 5 different chemical protective (CP) overgarments. The study was funded by the U.S. Army Natick Research, Development and Engineering Center (Natick). The application of the study was to provide the sponsoring agency sufficient data to compare 4 prototype garments to the existing Battledress Overgarment (BDO) and to select prototypes for further development and possible procurement. This report will describe step-by-step the methods and results of a biophysical evaluation of prototype Advanced Battledress Overgarments (ABDOs).

B. MILITARY RELEVANCE

In a memorandum for USARIEM from the Director, Individual Protection Directorate, Natick, concerning the ABDO program, the following statements were provided as background for the program: "Desert Shield/Storm identified the need for a lighter weight, less bulky chemical protective overgarment which offers heat reduction to the soldier. Additionally, the intelligence community has recognized the potential employment of aerosol based chemical agents as a realistic threat. As a result of these concerns, Congress mandated the initiation of an ABDO program. It was subsequently directed by the Vice Chief of Staff, Army as an accelerated two year development, procurement and evaluation project."

C. BACKGROUND

Military and defense industry literature (Hess and Russell, 1988; Smith, 1988; Hammick, 1991; Ewin, 1992) indicates the importance of CP clothing in modern military operations and reinforces an awareness that CP clothing impairs effective soldier performance during heat stress. Although many factors influence the selection of CP clothing, the physiological strain experienced by soldiers wearing CP clothing is a significant factor in performance degradation. This paper will primarily describe testing the physiological response of volunteer test subjects during exposure to heat stress while wearing CP overgarments in a closed Mission Oriented Protective Posture (MOPP-4) configuration. The specific objective is to determine if new CP clothing offers an advantage by reducing heat strain, relative to other CP clothing, including both standard issue and other prototypes. Other recent human studies of CP clothing include those of Vallerand et al. (1992); McLellan et al. (1992); Bomalaski and Constable, (1990a, b); Allsopp and Pethybridge, (1990). Recent papers on the evaluation of permeable CP clothing from USARIEM include Gonzalez et al. (1992), Santee and Wenger (1989), and Santee et al. (1992).

Numerous scientific studies (Goldman, 1963; Joy and Goldman, 1968; Goldman and Breckenridge, 1976; Speckman et al., 1988; Parker et al., 1987; Glumm, 1988; Knox et al., 1989) have established that CP clothing degrades soldier performance. A primary cause of this degradation is an increase in heat strain, which is incurred because CP clothing reduces heat loss to the environment. In a "warm" environment, the metabolic heat generated by an individual is often in excess of the quantity required to maintain homeostasis. Unless excess heat is transferred to the environment, an imbalance will occur, the body core will begin to warm, and the increasing level of thermal strain will affect performance. Clothing impacts heat exchange between a body and the environment by altering the rate of heat transfer by mechanisms of "wet" and "dry" heat transfer.

There are several factors that interact to determine the heat exchange between an individual and their environment. One factor is the environment. A combination of environmental parameters determines the potential for heat exchange between an individual and the environment: the temperatures of the air and any surfaces in contact

with the individual, air movement, radiation and humidity. An additional factor is the individual. Significant physical characteristics are mass and surface area. Significant physiological characteristics include body temperatures, activity (metabolism), and hydration (water balance). The final factor is clothing. In terms of heat exchange, clothing physically modifies the rate of heat exchange between the body and the environment. Chemical protective clothing is evaluated by measuring the physical properties of clothing that are biologically significant and by measuring the physiological differences in subject responses when the external environment is controlled.

There are three clothing properties that determine the degree to which clothing modifies the exchange of heat between individuals and their environment: 1) insulation, the resistance to "dry" heat exchange via convection and radiation, 2) evaporative cooling, achieved by the evaporation of sweat from the skin or clothing, and 3) ventilation and "pumping," the movement of air within the clothing and air exchange between the clothing spaces and the external environment that occurs in the dynamic state when an individual walks or runs while wearing a garment.

To design CP clothing that maintains an adequate level of chemical protection while reducing the level of heat strain experienced by the users requires the resolution of a paradox: good chemical protection is synonymous with poor heat exchange properties. Chemical protective clothing is specifically designed to minimize pumping and ventilation, the exchange of air between the outside environment and the air space layers inside the clothing, by sealing the openings at the neck, waist and cuffs of the zipped uniform so that specific agents cannot reach the skin surface. Other surfaces that would normally permit effective heat exchange, such as the face and hands, are also covered.

The most important mechanism for heat loss from the body is the evaporation of sweat. The most effective barrier against chemical agents is an impermeable layer, but clothing that is impermeable to chemicals is also a barrier to water vapor. Evaporated sweat that cannot pass through clothing may recondense, releasing the specific heat required to vaporize the sweat, and often accumulating inside the boots, mask or clothing, adding to the discomfort of the soldier. Insulation is closely related to fabric thickness. Clothing that is thicker, such as multi-layer fabrics and/or multiple clothing layers, is also better insulated. Better protection from chemicals essentially translates in greater susceptibility to discomfort, heat strain and injury.

The strategy for reducing heat strain while wearing CP clothing is to maximize heat loss to the environment by reducing insulation and/or increasing permeability to water vapor. For maximum protection, early versions of CP clothing were designed to be moisture and vapor impermeable. This was achieved by using butyl rubber-coated fabric. Butyl rubber-coated fabric is still used in the M6A2 hood and for protection during exposure to high chemical concentrations during handling of chemical munitions. To minimize heat strain and the resultant degradation of performance and potential heat casualties, newer CP garments have been designed to enhance evaporative heat transfer by replacing butyl rubber-coated materials with vapor permeable materials such as carbon impregnated foam. Virtually all present general issue CP clothing incorporate permeable materials that enhance evaporative heat transfer. Unfortunately, CP materials with enhanced vapor permeability are often thicker than butyl rubber-coated material, and gains in permeability may be at the cost of increased insulation.

As noted in the introduction, many factors influence the selection of CP clothing. The most obvious requirement is that the clothing provide adequate protection from chemical threat. The second most important requirement is that soldiers be able to perform their duties while wearing the CP uniform. Limited visibility, impedance of motion, weight, stiffness and heat strain are all factors that may adversely impact a soldier wearing CP clothing. Other factors in the selection of CP clothing include durability, cost and degradation during storage. It should be emphasized that the biophysical evaluation of clothing conducted at USARIEM encompasses only physiological responses to heat stress and the thermal properties of the clothing.

II. METHODS AND MATERIALS

A. GENERAL

Human testing with volunteer subjects provides information that cannot be obtained with physical models. Models lack the complexity of human thermoregulation. The skin temperature of humans is neither controlled at a constant setpoint nor constant over large areas. At this time, no physical model sweats like a human nor replicates the actual variation in core temperature that humans experience. As noted above, pumping occurs when an individual is active. The air spaces inside the clothing, particularly those between the skin and the clothing and between clothing layers, is compressed and expanded, changing the volume of those spaces.

B. OVERGARMENT DESCRIPTIONS

The original 6 prototype ABDO "systems" for this test consist of three types of outer material bonded to 2 different types of liner material with activated carbon. Those six combinations are listed in Table 1.

Table 1. Descriptions of ABDO prototypes and control

ensemble	shell	liner
A.	**7.0 oz NYCO (control)**	**superactivated carbon foam, 90 mil**
B.	4.5 oz NYCO twill	superactivated carbon foam, 50 mil
C.	**4.5 oz NYCO twill**	**Von Blücher carbon spheres, 180 $g \cdot m^{-2}$**
D.	**6.0 oz NYCO ripstop**	**superactivated carbon foam, 50 mil**
E.	**6.0 oz NYCO ripstop**	**Von Blücher carbon spheres, 80 $g \cdot m^{2}$**
F.	ECWCS/Gore-tex©	superactivated carbon foam, 50 mil
G.	**ECWCS/Gore-tex©**	**Von Blücher carbon spheres, 180 $g \cdot m^{-2}$**

Bold-faced garments selected for human testing.

The current issue BDO is described as a 7 oz NYCO shell with a 90 mil carbon foam liner. NYCO is a nylon-cotton blend. Twill is a characteristic fabric weave. Ripstop is a fabric that has cross reinforcements in the weave that prevent tears and rips from enlarging. The current Extended Cold Weather Clothing System (ECWCS) includes outer shell garments of Gore-tex material. In the list of ABDO materials, ECWCS refers to the fabric used for the outer shell garment. Gore-tex© is a proprietary technology that incorporates a polytetrafluoroethylene (PTFE) layer. It is inaccurately described as "breathable" because the material is permeable to water in the vapor state, but acts as a barrier to water in liquid form. Activated carbon absorbs contaminants from air that may pass through the outer material. Von Blücher (or Saratoga) incorporates a proprietary carbon sphere technology. Wenger and Santee (1988) conducted a prior study of prototype CP overgarments which utilized Gore-tex© and Von Blücher materials in different material systems. The present prototypes are more refined developments relative to those earlier systems. The prototypes have separate hoods or balaclavas rather than the butyl rubber M6A2 type hood. All prototype hoods are compatible with the M-40 mask.

C. PHYSIOLOGICAL TESTING WITH HUMAN SUBJECTS

1. Environmental Chamber Conditions

The selection of environmental chamber test conditions is important. Only 2 environments were chosen. The actual conditions were a compromise between a desire to simulate specific environments (hot desert and temperate summer) and to manipulate the test environments to elicit the most definitive responses from the subject population that would not be totally intolerable for the test volunteers. The selection of the chamber environments was coordinated with the test sponsor. The 2 test environments were condition (A) 30°C (86°F), 50% rh and condition (B) 38°C (100°F), 20% rh. Wind speeds were 1.1 $m \cdot s^{-1}$ (2.5 mph) for the 30°C environment and 3.0 $m \cdot s^{-1}$ (6.5 mph) for the 38°C environment. No solar simulation was used in this study. Test conditions are summarized in Table 2. The first (A) environment represents a warm, temperate environment. This test environment has been proposed for a chamber study of the Soldier Integrated Protective Ensemble (SIPE) system. The use of the same environment for the ABDO and SIPE evaluations to provide continuity between CP clothing tests was

specifically requested by the sponsor. The reduced wind speed and higher humidity will reduce heat loss by convection and evaporation, but these disadvantages will be partially offset by the reduced air temperature. The second (B) test condition represents a hot-dry environment, which maximizes evaporative heat loss. Garments with lower insulation lose heat more rapidly by convection at higher wind speeds, and garments with greater moisture permeability allow more sweat to evaporate. The heat gain from the environment via convection, when environmental temperatures (air and chamber walls) are greater than surface temperatures, may be partially offset by a slight increase in radiative heat loss.

Table 2. Summary of test conditions for ABDO prototype test (4 prototypes plus BDO control)

Environment A	
wind speed	1.1 $m \cdot s^{-1}$ (2.5 mph)
work rate	1.56 $m \cdot s^{-1}$ (3.5 mph)
air temperature	30°C (86°F)
humidity	50% rh (18°C T_{dp})
estimated WBGT	24°C (75°F)
Environment B	
wind speed	3.0 $m \cdot s^{-1}$ (6.5 mph)
work rate	1.56 $m \cdot s^{-1}$ (3.5 mph)
air temperature	38°C (100°F)
humidity	20% rh (11°C T_{dp})
estimated WBGT	26°C (79°F)

2. Test Methods

Testing of volunteer subjects wearing 4 prototype ABDOs plus the present issue BDO was conducted at Natick in the tropic environmental chamber. The overgarments selected for testing were the 4.5 oz NYCO shell with a Von Blücher liner (P1S), the 6.0 oz NYCO shell with a Von Blücher liner (P2S), the 6.0 oz NYCO shell with 50 mil foam

liner (P2F) and the Gore-Tex© shell with a Von Blücher liner (S3). The control was the Woodland BDO with 90 mil foam liner.

Subjects wore the overgarments over underwear in MOPP-4 configuration with CP mask, gloves and overboots. For the 4 prototype garments, the mask was the M-40 and the M-17A1 was worn with the BDO. The filters were removed from the masks to avoid the confounding impact of mask breathing resistance. The objective of the study was to compare performance between overgarments rather than any non-thermal factors attributable to the masks.

The basic test design was derived from Gonzalez et al. (1989, 1992) and used subsequently in Santee et al. (1992). The protocol consisted of 6 consecutive days of acclimation and 10 days of regular garment testing in MOPP-4, broken into two 5-day segments. Each of the 10 garment test periods consisted of 100 minutes of treadmill exercise while wearing different CP overgarments in the MOPP-4 configuration during exposure to environmental heat stress. Test variables were environment (2) and clothing (5 garments, including the control BDO) as independent variables; and change in rectal, mean skin and mean body temperatures, evaporative water loss (sweat) and endurance time as dependent variables.

3. Volunteer Population

Thirteen healthy young male volunteers (ages 18-35 years) from the Natick volunteer subject population and U.S. Marine Corps Reserves (25th Marines) were recruited for the study. Subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research. Prior to any experimental testing, all subjects were medically screened and familiarized with all test procedures.

4. Instrumentation and Safety Limits

Volunteers were instrumented with a rectal temperature probe, 4 surface skin temperature sensors, and an EKG telemetry system to monitor heart rate. During most of the garment testing an additional heart rate monitor was added to the instrumentation. The safety procedures for this study conformed to the limits specified in the USARIEM

Type Protocol for Human Research Studies in the Areas of Thermal, Hypoxic and Operational Stress, Exercise, Nutrition and Military Performance (May, 1992). For both acclimation and garment testing, the physiological test limits were 102.2°C or sustaining 90% of maximum heart rate for 5 minutes. Volunteers were also withdrawn from a test session on the basis of severe heat strain symptoms (temporary loss of consciousness, headaches, chest pains, nausea), or other non-heat related reasons ("shin splints," foot blisters, chafing, non-heat rashes, non-heat illness) at the direction of a medical monitor, test observer or the test volunteer's personal decision.

5. Physiological Test Variables

The physiological measurements that were collected as test variables were core temperature, surface skin temperatures, and pre- and post-test body weights. Core temperature was measured as rectal temperature (T_{re}). As test statistics, the calculated change in rectal temperature ($\Delta T_{re} \cdot min^{-1}$) from the initial rise to subject termination for each day is better than T_{re} because of the combined intra- and intersubject variability in daily baseline T_{re}. Evaporative cooling was quantified by using subject weights to calculate a water balance. The difference between pre- and post-test nude weights provides a measure of the water lost as sweat (W_L). The evaporative water loss (E_{sw}) is simply the difference between pre- and post-test clothed weights. The rate of evaporative water loss ($\Delta E_{sw} \cdot min^{-1}$) was calculated by dividing the evaporative loss by time. The ratio of the sweat evaporated to the gross water loss from the body is the efficiency of sweating. Test sessions were of a fixed duration--100 minutes of walking on the treadmill after a 20-minute standing baseline period--so "endurance" refers to the length of participation in the test session by a subject. One hundred minutes can be readily converted into a percentage of task completion, which is a more accurate description of the test result. Heart rates were recorded for safety monitoring (U.S. Army Research Institute of Environmental Medicine, 1992) and are an indicator of subject strain. However, for the purpose of discriminating between overgarments, changes in core temperature and sweat rate have been more reliable physiological parameters.

6. Acclimation

Volunteers were heat acclimated for 6 days prior to MOPP-4 garment testing by walking on a level treadmill at 1.56 $m \cdot s^{-1}$ (3.5 mph) with environmental test chamber

conditions at 49°C (120°F), 20% rh and 1.1 $m \cdot s^{-1}$ wind speed. Their 120-minute exposure was divided into a 10-minute standing baseline and two 50-minute walk sessions separated by a 10-minute rest period. Water was provided ad libitum. Acclimation methods are derived from Pandolf et al., 1988. During the acclimation period, metabolic rates were measured by collecting expired gases in Douglas bags and analyzed by open circuit spirometry (Pandolf et al., 1988). The subjects wore gym shorts and boots during acclimation.

7. Pre-test

Because only 8 volunteers encumbered with the MOPP-4 ensembles can be tested on the treadmill at one time, the volunteer population was divided into 2 test groups. To control for circadian effects, one group always tested in the morning and the second group always in the afternoon. During garment testing, volunteers drank 400 ml of water prior to dressing for testing, but received no additional water until testing was completed. After being weighed nude, donning undershorts and instrumentation, test volunteers dressed in a MOPP-4 ensemble consisting of:

overgarment over underwear (shorts and t-shirt)
boots and socks
CP overboots and glove set
hood, M40 or M17 CP mask without filters

The fully clothed and instrumented subjects were weighed just prior to entering the environmental chambers to obtain a pre-exercise clothed weight.

8. Chamber Testing

On test days, volunteers entered the test chamber and were connected to the data acquisition system. They stood for 20 minutes to establish a data baseline, then they began walking on the level treadmills at 3.5 mph. Volunteers walked without interruption for 100 minutes, unless they reached the physiological limits selected for this study (39°C [102.2°F] or 90% of maximum heart rate), voluntarily ended their participation or were removed by the test observers or the medical monitor for other medical or technical reasons.

The treadmills were run at 1.56 $m \cdot s^{-1}$ (3.5 mph) and there was zero grade. The treadmill speed corresponds to a level of moderate work intensity (325-500 W) in MOPP-2 to MOPP-4 (Appendix B, Glenn et al., 1990). As noted above, the 2 test environments were condition (A) 30°C (86°F), 50% rh, with a 1.1 $m \cdot s^{-1}$ (2.5 mph) wind speed and condition (B) 38°C (100°F), 20% rh, with a 3.0 $m \cdot s^{-1}$ (6.5 mph) wind speed. Clothing consisted of MOPP-4 ensembles worn over underwear. The M-40 mask was worn with the prototype overgarments, and the M-17A1 was worn with the BDO overgarment. The presentation of clothing was counter-balanced to minimize time effects as per Table 3.

Table 3. ABDO Test schedule

Day	environment	AM uniform	PM uniform
1	30°C, 50% rh	P2S	P1S
2	30°C, 50% rh	S3	P2F
3	30°C, 50% rh	P2F	BDO
4	30°C, 50% rh	BDO	S3
5	30°C, 50% rh	P1S	P2S
6	38°C, 20% rh	P1S	P2S
7	38°C, 20% rh	BDO	S3
8	38°C, 20% rh	P2F	BDO
9	38°C, 20% rh	S3	P2F
10	38°C, 20% rh	P2S	P1S

BDO	Woodland battledress overgarment with 90 mil foam liner
P1S	4.5 oz NYCO shell with a Von Blücher liner
P2S	6.0 oz NYCO shell with a Von Blücher liner
P2F	6.0 oz NYCO shell with 50 mil foam liner
S3	Gore-Tex© shell with a Von Blücher liner

9. Post-chamber Measurements

Upon exiting the chamber, the volunteers' post-exercise clothed weights were measured. After undressing and removal of instrumentation, they were weighed nude to obtain the post-exercise nude weight.

III. RESULTS

A. RESULTS FROM HUMAN TESTING

1. Volunteer Subject Parameters

The study was initiated on 10 May 1993 with 13 subjects (8 USMC reservists and 5 U.S. Army volunteers). After acclimation at 120°F, 20% rh and 2.5 mph wind speed for 6 days, 1 subject was unable to continue testing. Garment testing began on 17 May 1993 with 12 volunteers. Table 4 presents descriptive statistics for the initial test population. The test environment for the first 5 days was 86°F, 50% rh and 2.5 mph wind speed.

Table 4. Mean subject parameters (n=12)

	Height (cm)	Weight (kg)	Age (yr)	Metabolic rate* (W)
mean	176	76.8	25	434
s.d.	8	11.6	5	57
range	158-183	63.5-97.8	18-35	347-459

* Walking on level treadmill with boots at 3.5 $m \cdot s^{-1}$, average 2 measurements (one missing data point).

Two volunteers were removed from the study during the first week of garment testing in accordance with USARIEM Response Protocol for Human Subject Medical Questions/ Emergencies (8 FEB 93) following incidence of chest pain or temporary blackout. Ten volunteers began the second test week, which consisted of 5 days of testing at 100°F with a 6.5 mph wind speed.

2. General Results

Primary test results consisted of three types of data: total walking time (endurance), change in rectal temperature (ΔT_{re}) and water loss data (net evaporative water loss and efficiency or ratio of sweat to evaporative water loss). Data for endurance were not totally reliable because, as stated before, volunteers frequently withdrew for non-heat related problems such as shin splints, blisters and chafing. Those data could not be considered legitimate endurance times as a function of an incremental increase in core temperature caused by a given overgarment. Such data were eliminated from those data sets. For water loss and ΔT_{re}, data for volunteers who walked on the treadmill for less than 40 minutes were also not included in the statistical analysis. Test results consisted of total walk or endurance time, gross or total sweat loss, effective evaporative water loss, sweating efficiency (the ratio of evaporative loss to gross sweat loss) and rate of change in rectal temperature. The tables for each variable (Tables 5-9) present descriptive statistics for mean, standard deviation and population size.

3. Statistical Methods

Statistical analysis consisted of repeated measures multiple analysis of variance (MANOVA). The post-hoc test was Tukey's Studentized Range Test, with one exception. The post-hoc analysis of ΔT_{re} in the 86°F environment used both the Duncan's multiple range test and Student-Newman-Keuls test. The MANOVA calculates an f-test statistic to determine if the overall results are significant for all uniforms and all subjects within a test environment. If the overall differences are significant, then the differences between individual pairs are tested with the post-hoc test for significance. The level of significance for all tests was $\alpha \leq 0.05$. Each environment was treated separately because the environments varied in temperature, humidity and wind speed. In addition, because a different mask was used for the BDO tests, data sets were analyzed with (5 uniforms) and without (4 uniforms) the BDO data. In some cases, eliminating the BDO data increased the test populations, thereby eliminating some Type II errors. For the endurance time variable, for the data set without the BDO control, a significant difference was found between P1S and P2S.

4. Results by Variable Type

a. Endurance Times. These data (Table 5) are derived from the total walking time of each test volunteer. Only data from subjects who where either terminated from reaching a physiological limit (maximum rectal temperature or heart rate) or who clearly demonstrated a physiological response to heat strain were included. "Endurance times" are frequently quoted as the most "mission relevant" statistic, but unfortunately, endurance values from chamber studies do not translate directly into field performance. Chamber studies are essentially cold starts from thermoneutral conditions rather than the imposition of MOPP-4 under already stressful field conditions.

Table 5. Endurance times (minutes)

	BDO	P1S	P2S	P2F	S3
86°F, 50% rh, 2.5 mph	**62**	**79**	**80**	74	72
(s.d.)	12	10	9	8	7
(n)	4	6	9	7	8
100°F, 20% rh, 6.5 mph	**57**	**72**	**63**	**59**	**50**
(s.d)	5	7	5	8	4
(n)	8	12	6	7	6

Bold-face indicates that garments differed significantly from other garments when overall relationship was significant (see para 11).
86°F environment, overall p=0.0172, significant pairs are BDO-P1S, BDO-P2S.
100°F environment, overall p=0.0002, significant pairs are S3-P1S, S3-P2S, BDO-P1S, P2F-P1S, special case P2S-P1S (4 uniforms, no BDO).

BDO	Woodland battledress overgarment with 90 mil foam liner
P1S	4.5 oz NYCO shell with a Von Blücher liner
P2S	6.0 oz NYCO shell with a Von Blücher liner
P2F	6.0 oz NYCO shell with 50 mil foam liner
S3	Gore-Tex© shell with a Von Blücher liner

At 86°F, the walking endurance time was significantly less for the BDO relative to both P1S and P2S (Figure 1). Walking time was significantly greater at 100°F for P1S than P2F, BDO or S3, and subjects walked significantly longer while wearing P2S than S3 (Figure 2). When the BDO was not included in the data set, there was also a significant difference between P2S and P1S.

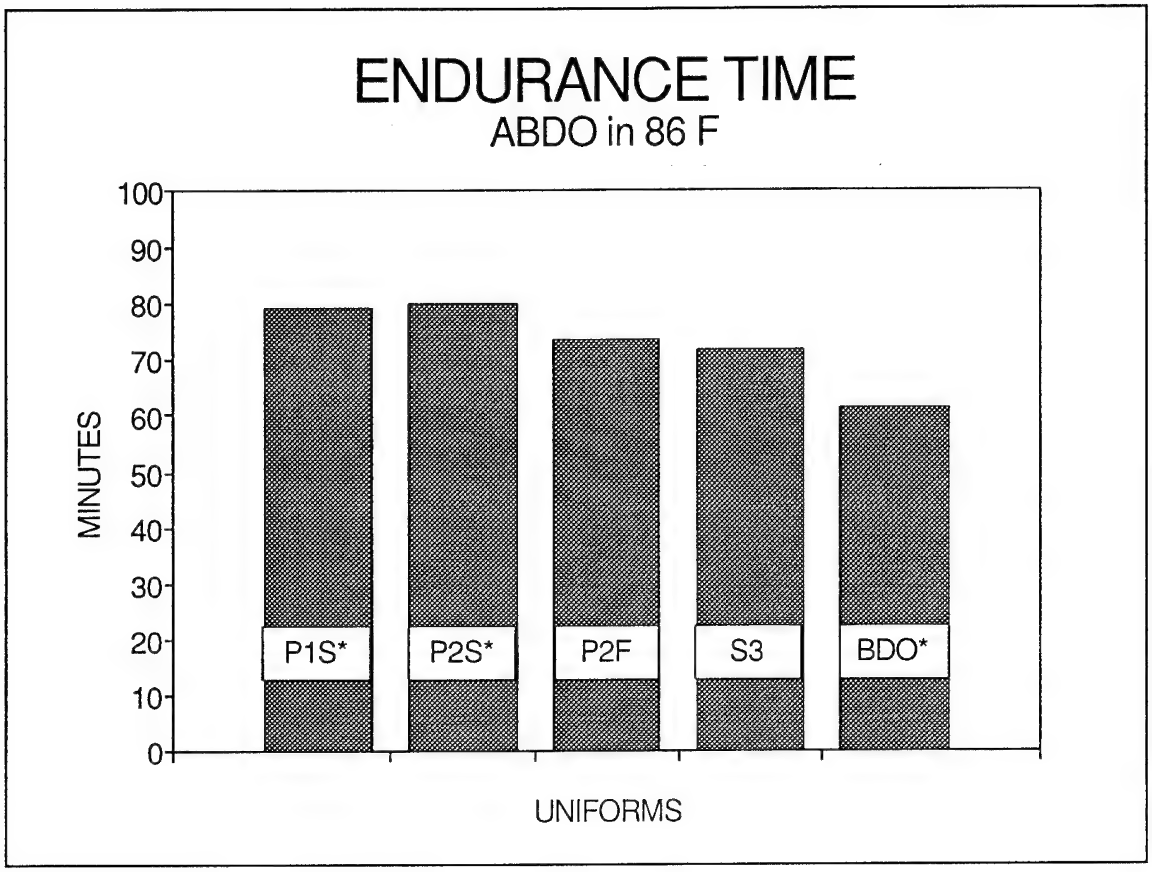

Figure 1. Comparison of endurance times in a warm environment.
* Indicates significant difference between prototype and BDO.

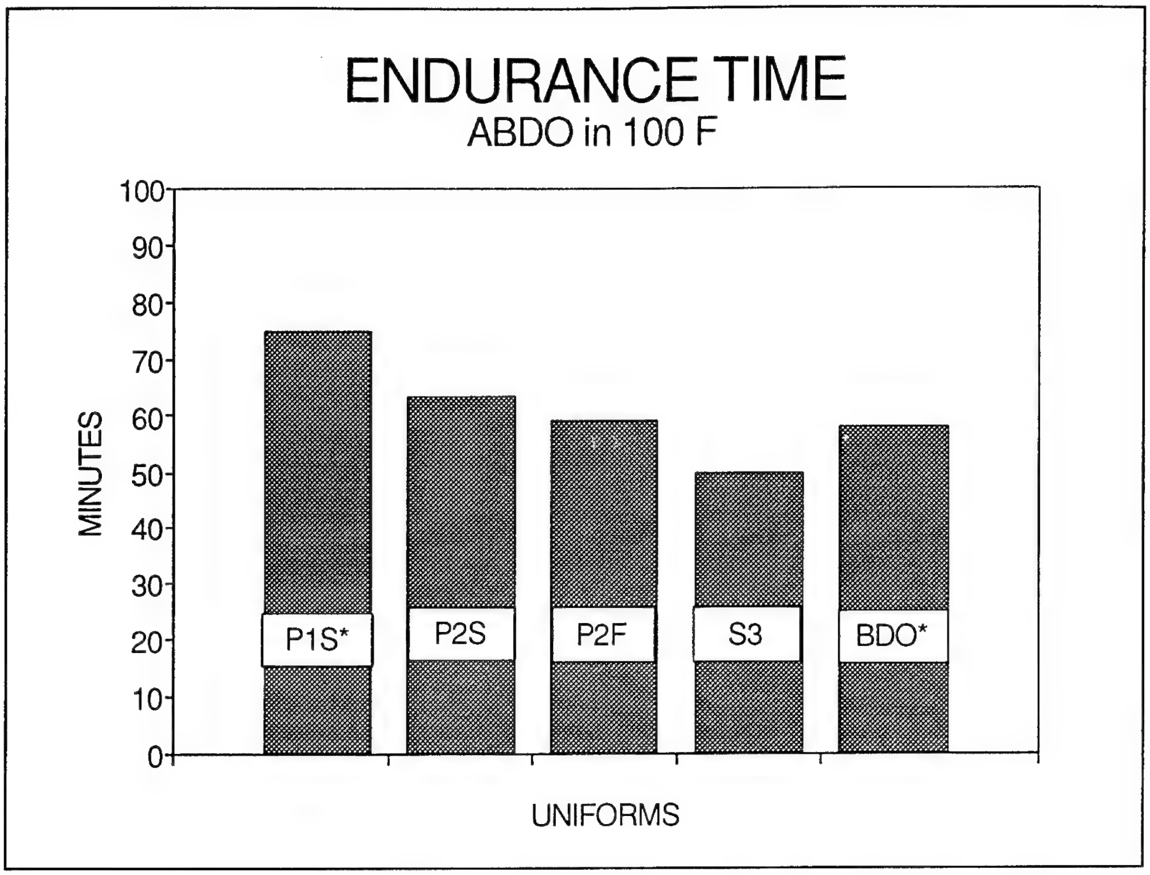

Figure 2. Comparison of endurance times in a hot, dry environment.
* Indicates significant difference between prototype and BDO.

b. Rate of Increase in Rectal Temperature. These data (Table 6) are calculated for the rate of rise, normalized for a 1-hour interval ($\Delta T_{re} \cdot h^{-1}$), during walking. A higher rate of heat gain incurs greater heat strain and is therefore a disadvantage. There is often a lag in the response of rectal temperature relative to the onset of activity. To eliminate that concern, the initial or start point for calculation of the rate of increase is at 20 minutes into the walking interval rather than at the beginning of the walking activity.

Table 6. Rate of change in rectal temperature ($\Delta T_{re} \cdot h^{-1}$)

	BDO	P1S	P2S	P2F	S3
86°F, 50% rh, 2.5 mph					
ΔT_{re}	**2.03**	**1.55**	**1.58**	1.83	1.89
(s.d.)	0.44	0.32	0.25	0.43	0.30
(n)	8	9	10	9	9
100°F, 20% rh, 6 mph					
ΔT_{re}	**2.43**	**1.76**	**2.00**	**2.25**	**2.92**
(s.d)	0.37	0.38	0.21	0.40	0.37
(n)	8	8	8	7	6

Bold-face values differed significantly from other garments.
86°F environment, overall $p=0.0290$, significant pairs are BDO-P1S, BDO-P2S.
100°F environment, overall $p<0.0001$, significant pairs are S3-P1S, S3-P2S, S3-P2F, BDO-P1S.

BDO	Woodland battledress overgarment with 90 mil foam liner
P1S	4.5 oz NYCO shell with a Von Blücher liner
P2S	6.0 oz NYCO shell with a Von Blücher liner
P2F	6.0 oz NYCO shell with 50 mil foam liner
S3	Gore-Tex© shell with a Von Blücher liner

In the 86°F environment, because the rate of increase in $\Delta T_{re} \cdot h^{-1}$ was smaller, the P1S and P2S overgarments were significantly better than the BDO overgarment (Figure 3). Other differences in the 86°F environment were not significant. At 100°F, the rate of increase in rectal temperature ($\Delta T_{re} \cdot h^{-1}$) for S3 was significantly higher than the rate for P1S, P2S or P2F, and the BDO rate of increase was significantly higher than the rate for P1S (Figure 4).

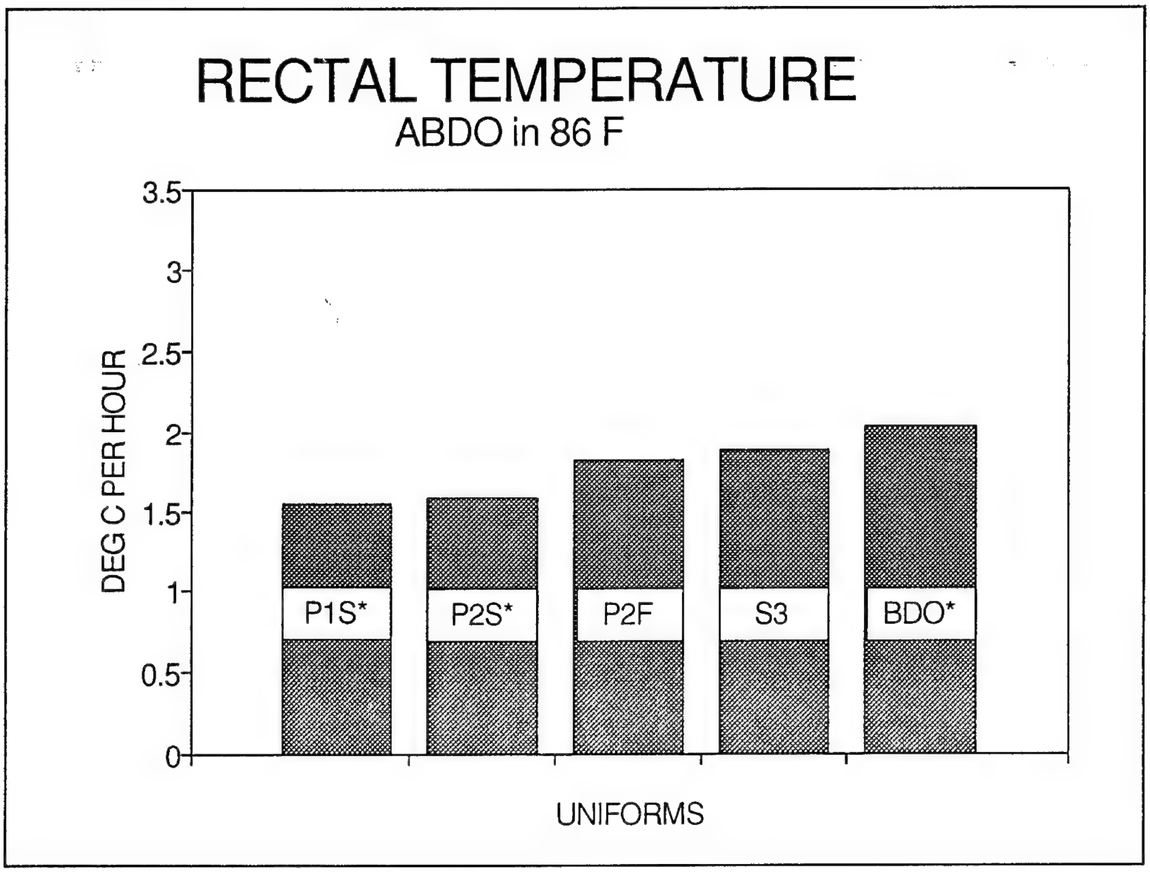

Figure 3. Comparison of rate of change in rectal temperature in a warm environment.
* Indicates significant difference between prototype and BDO.

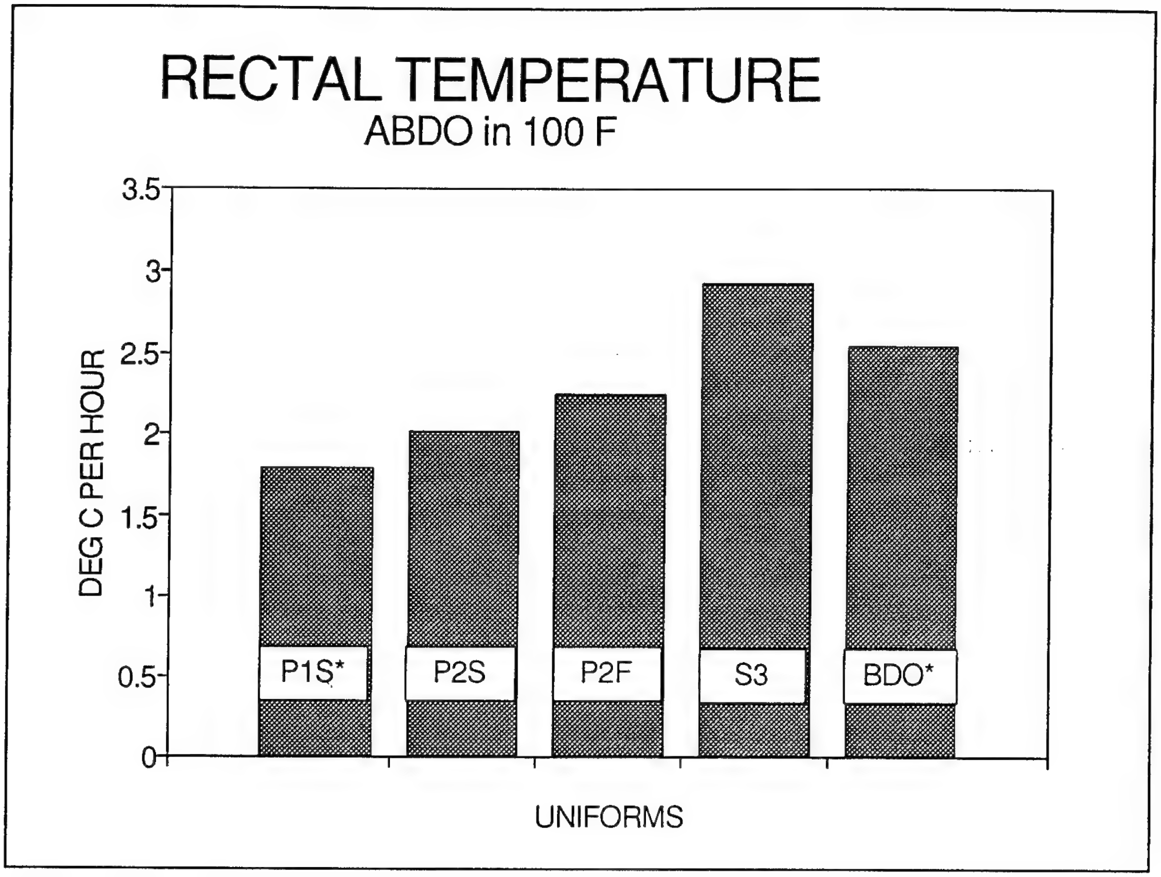

Figure 4. Comparison of rate of change in rectal temperature in a hot, dry environment.
* Indicates significant difference between prototype and BDO.

c. Mean Body Temperature. As in the case for rectal temperature (Table 7), a higher rate of heat increase represents greater heat strain and is a disadvantage. The weighted average of T_{re} (0.8) and mean T_{sk} (0.2) adjusts for individual differences in thermoregulation by considering the effect of differences in total skin temperature under a garment. There are more missing data in this set because the loss of a single surface thermocouple (out of three) eliminates the entire data set. These data are also normalized for a 1-hour interval ($\Delta T_b \cdot h^{-1}$).

Table 7. Rate of increase in mean body temperature ($\Delta T_b \cdot h^{-1}$)

	BDO	P1S	P2S	P2F	S3
86°F, 50% rh, 2.5 mph					
ΔT_b	**2.04**	**1.54**	**1.47**	1.80	1.71
(s.d.)	0.38	0.34	0.25	0.42	0.27
(n)	8	9	9	8	8
100°F, 20% rh, 6 mph					
ΔT_b	**2.44**	**1.63**	**1.84**	**2.22**	**2.66**
(s.d)	0.20	0.30	0.25	0.41	0.38
(n)	7	5	5	7	5

Bold-face indicates that garments differed significantly from other garments when overall relationship was significant.
86°F environment, overall p=0.0106, significant pairs are BDO-P1S, BDO-P2S.
100°F environment, overall p<0.0001, significant pairs are S3-P1S, S3-P2S, BDO-P1S, BDO-P2S, P2F-P1S.

BDO	Woodland battledress overgarment with 90 mil foam liner
P1S	4.5 oz NYCO shell with a Von Blücher liner
P2S	6.0 oz NYCO shell with a Von Blücher liner
P2F	6.0 oz NYCO shell with 50 mil foam liner
S3	Gore-Tex© shell with a Von Blücher liner

In the 86°F environment, because the rate of increase in $\Delta T_b \cdot h^{-1}$ was smaller, the P1S and P2S overgarments were significantly better than the BDO overgarment (Figure 5). Other differences in the 86°F environment were not significant. In the 100°F environment, the rate of increase in mean body temperature ($\Delta T_b \cdot h^{-1}$) for the S3 and BDO overgarments were significantly higher than P1S or P2S (Figure 6). The rate of increase for P2F was significantly higher than the rate of increase for P1S.

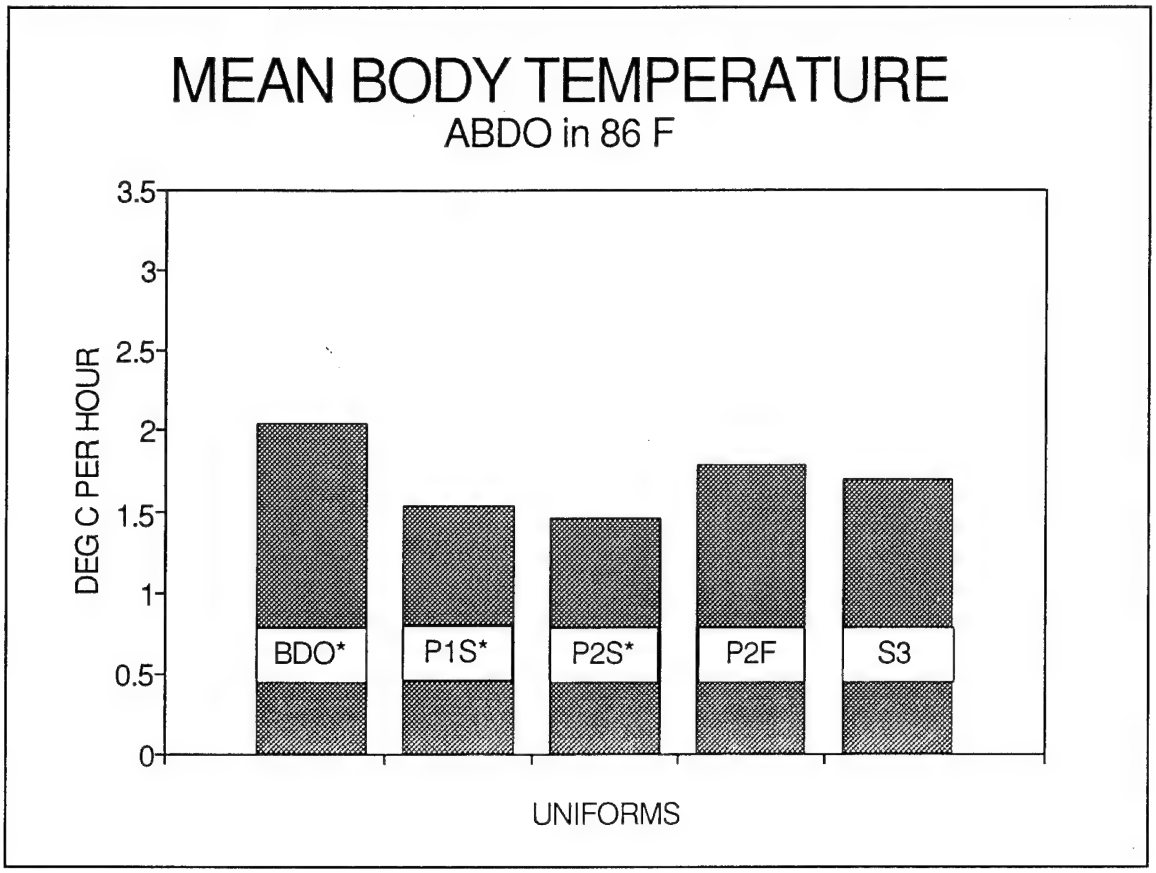

Figure 5. Comparison of rate of change in mean body temperature in a warm environment. * Indicates significant difference between prototype and BDO.

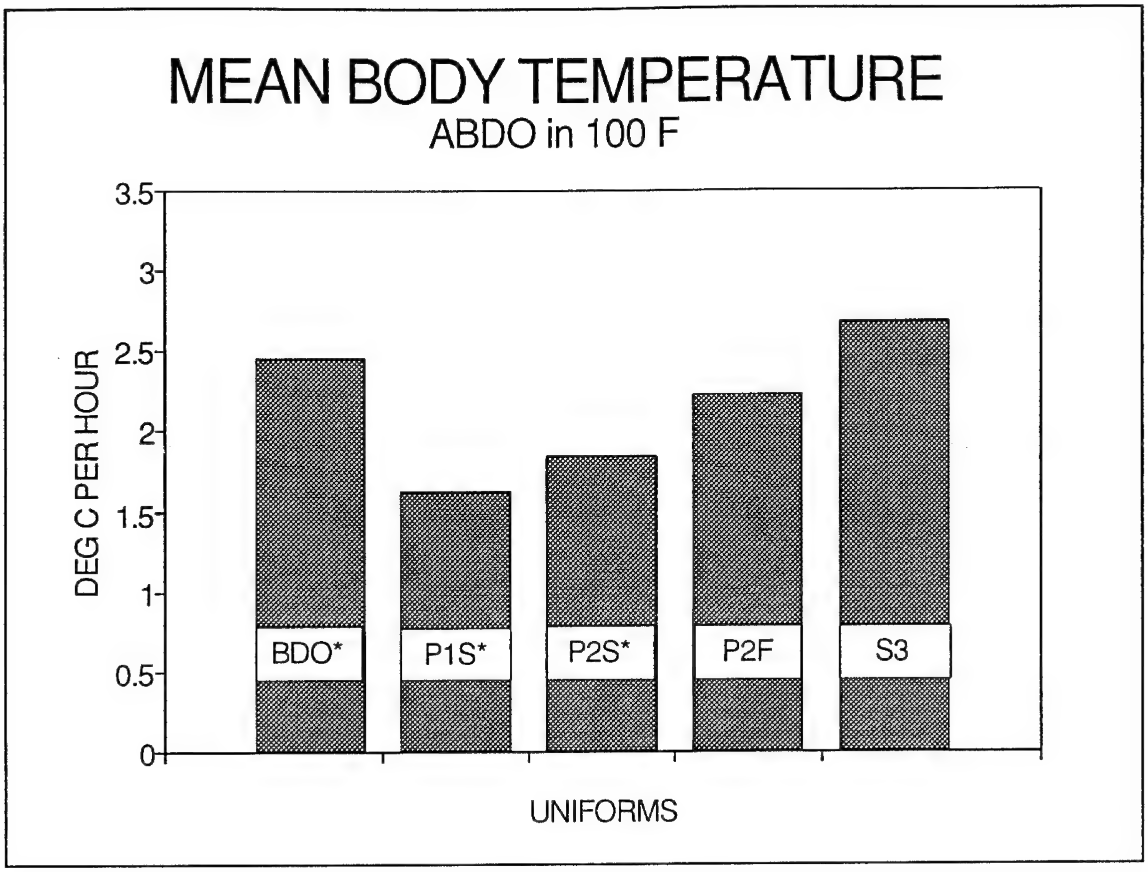

Figure 6. Comparison of rate of change in mean body temperature in a hot, dry environment. * Indicates significant difference between prototype and BDO.

d. Net Evaporative Water Loss. These data (Table 8) are derived from the change in clothed weight of test volunteers during the walking period and represent the amount of water lost to the environment. Only water vapor lost to the environment contributes to evaporative cooling.

Table 8. Rate of evaporative water loss to the environment ($g \cdot min^{-1}$)

	BDO	P1S	P2S	P2F	S3
86°F, 50% rh, 2.5 mph					
E_{sw}	7.0	8.0	8.3	7.8	7.6
(s.d.)	2.2	1.5	2.7	2.4	1.6
(n)	8	9	10	9	9
100°F, 20% rh, 6 mph					
E_{sw}	9.7	12.8	12.3	10.7	10.4
(s.d)	3.3	3.0	2.2	1.3	2.6
(n)	7	7	7	6	6

BDO	Woodland battledress overgarment with 90 mil foam liner
P1S	4.5 oz NYCO shell with a Von Blücher liner
P2S	6.0 oz NYCO shell with a Von Blücher liner
P2F	6.0 oz NYCO shell with 50 mil foam liner
S3	Gore-Tex© shell with a Von Blücher liner

e. Total Water Loss. These data (Table 9) are derived from the change in nude body weight during the study. Total or gross water loss (W_L) is in response to the level of thermal strain and is a relative indication of dehydration during the exercise period. W_L is an important parameter for thermal strain because sweating is a response to thermal stress and water loss is a direct measure of dehydration.

Table 9. Gross or total water loss to the environment ($g \cdot min^{-1}$)

	BDO	P1S	P2S	P2F	S3
86°F, 50% rh, 2.5 mph					
W_L	25.3	22.5	23.1	26.3	25.7
(s.d.)	3.0	4.8	5.0	4.5	3.5
(n)	8	9	10	9	9
100°F, 20% rh, 6 mph					
W_L	29.8	26.3	28.4	29.4	32.4
(s.d)	6.5	5.7	5.5	5.6	5.2
(n)	7	7	7	6	6

BDO	Woodland battledress overgarment with 90 mil foam liner
P1S	4.5 oz NYCO shell with a Von Blücher liner
P2S	6.0 oz NYCO shell with a Von Blücher liner
P2F	6.0 oz NYCO shell with 50 mil foam liner
S3	Gore-Tex© shell with a Von Blücher liner

f. Sweating Efficiency. These data (Table 10) are derived from the ratio of evaporative water loss to gross body water loss. Efficiency represents the ratio of cost (dehydration) to benefit (evaporative cooling). In response to heat strain, the body sweats to increase evaporative cooling. However, due to the combination of clothing resistance, often expressed as water vapor permeability, and the humidity of the surrounding environment, not all sweat is evaporated into the environment. Gross sweat represents the body's physiological effort to increase evaporative heat loss, whereas net evaporative water loss represents the actual level of evaporative cooling.

Table 10. Sweating efficiency (percentage of evaporative water loss relative to gross [body] water loss)

	BDO	P1S	P2S	P2F	S3
86°F, 50% rh, 2.5 mph					
% EFF	27.9	35.8	35.6	30.6	29.5
(s.d.)	8.4	4.4	8.7	8.9	4.2
(n)	8	9	10	9	9
100°F, 20% rh, 6 mph					
% EFF	**33.2**	**49.6**	**43.5**	**36.9**	**31.9**
(s.d)	10.4	6.8	4.6	4.9	3.1
(n)	7	7	7	6	6

Bold-faced values differed significantly from other garments.
86°F environment, overall p=0.0840 (not significant).
100°F environment, overall p<0.0001, significant pairs are S3-P1S, S3-P2S, BDO-P1S, P2F-P1S.

BDO	Woodland battledress overgarment with 90 mil foam liner
P1S	4.5 oz NYCO shell with a Von Blücher liner
P2S	6.0 oz NYCO shell with a Von Blücher liner
P2F	6.0 oz NYCO shell with 50 mil foam liner
S3	Gore-Tex© shell with a Von Blücher liner

At 100°F, the efficiency of sweating (ratio of sweat evaporated to the external environment to the gross body water loss) was greater for P1S than P2F, the BDO or S3, and the efficiency was greater for P2S than S3 (Figure 7). There were no significant differences in the 86°F environment (Figure 8).

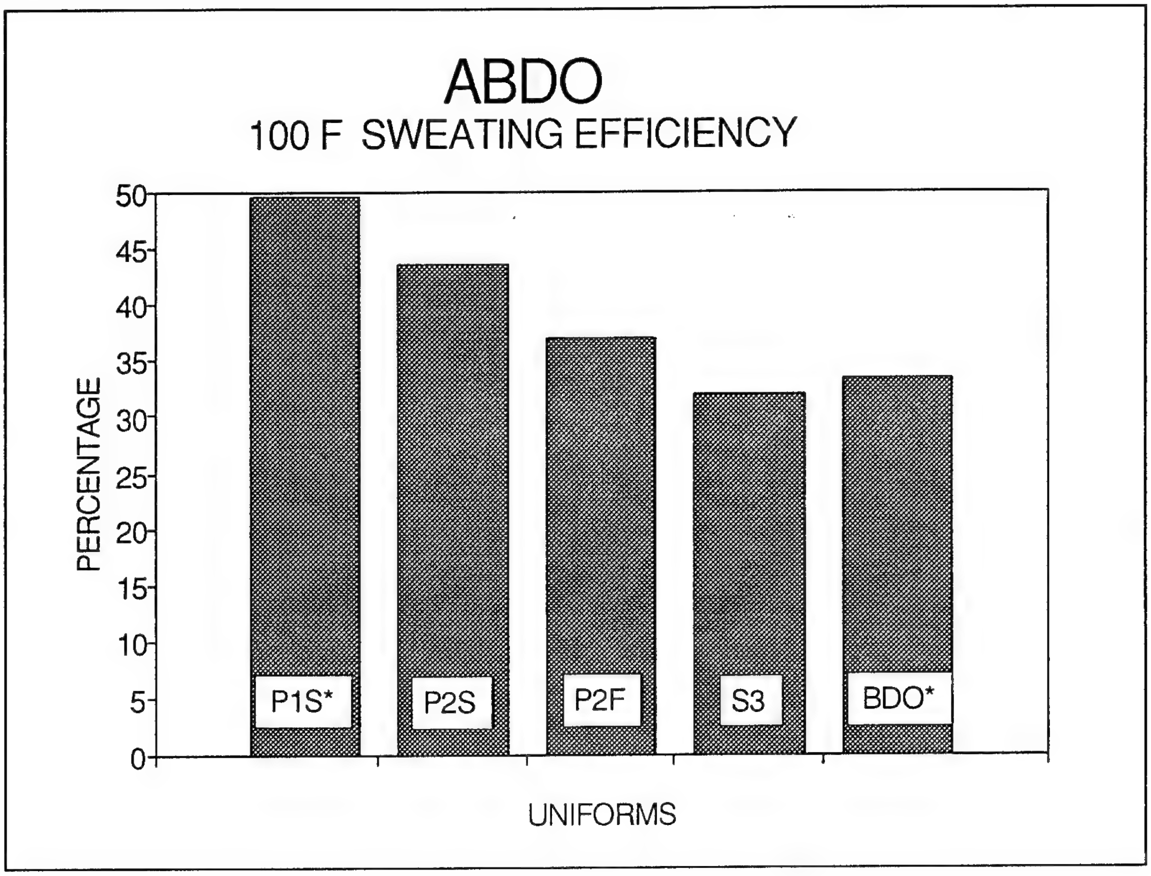

Figure 7. Sweating efficiency in a hot, dry environment.

* Indicates significant difference between prototype and BDO.

B. COMPARISON OF MODELING AND HUMAN TEST RESULTS

The two following figures (8,9) compare human test data to previous USARIEM heat strain modeling results for the same uniforms in similar environments (Gonzalez, 1994). All significant results from the human testing were analogous to the results predicted by modeling. Human test data for the 86°F and 100°F environments are represented by the shaded bars, and the calculated data for 82°F and 104°F environments are represented by open bars.

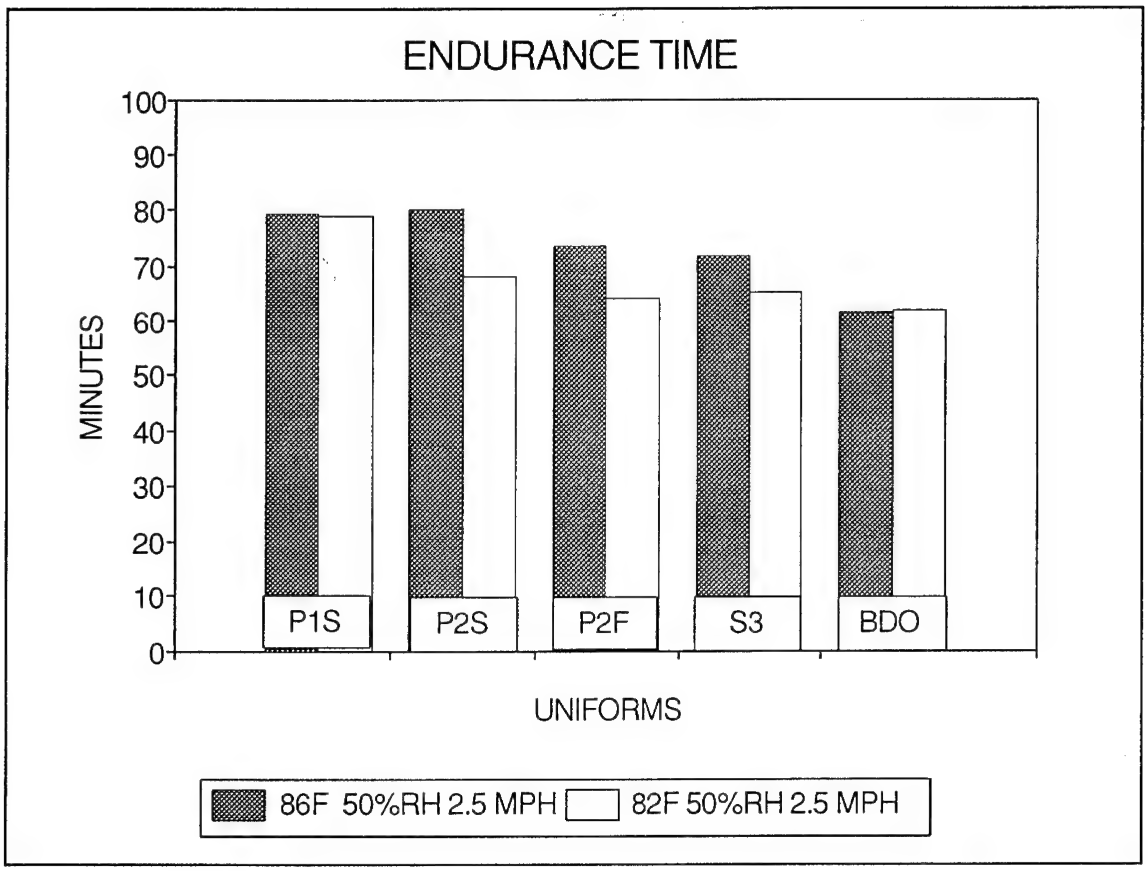

Figure 8. Comparison of endurance times to calculated work times in a warm environment.

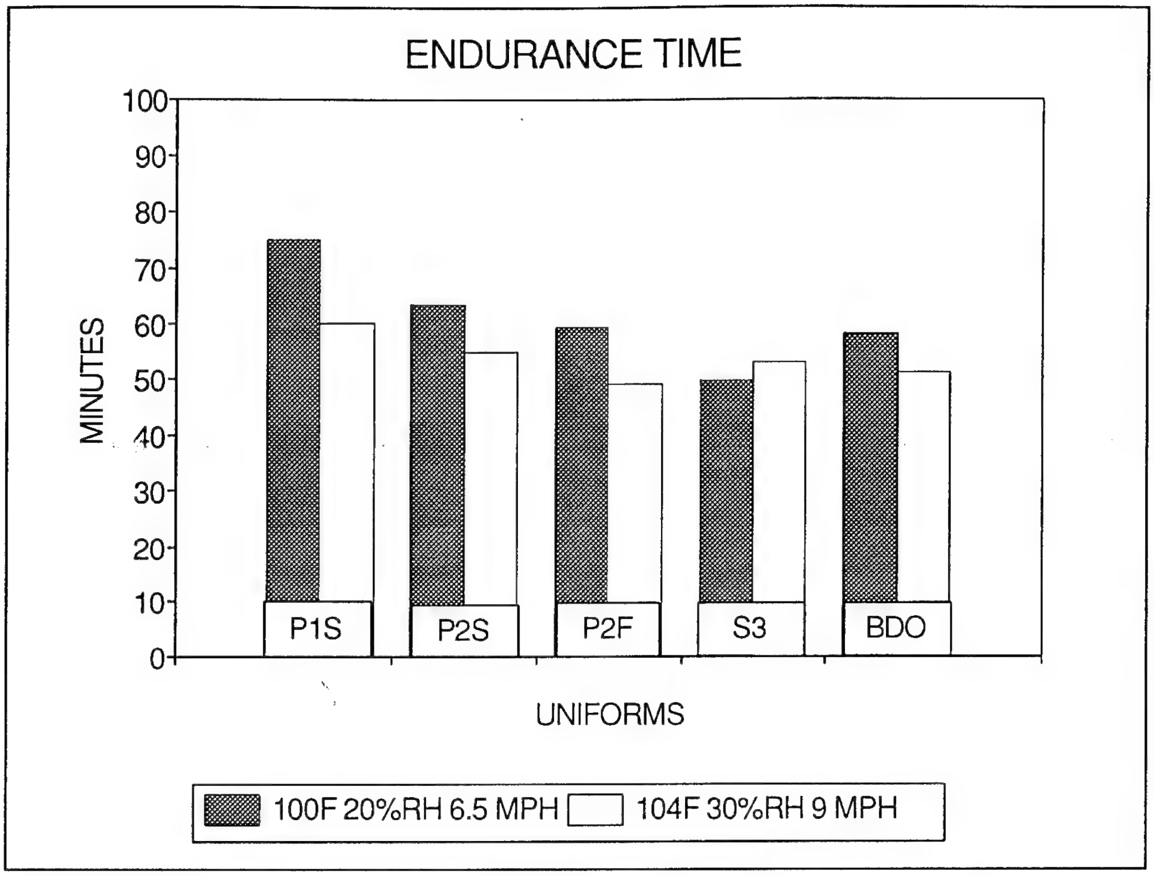

Figure 9. Comparison of endurance times to calculated work times in a hot, dry environment.

IV. DISCUSSION

A. COMPARISON BETWEEN OVERGARMENTS

1. Comparison Between Individual Overgarments

When the test subjects wore the ECWCS/Gore-tex© PTFE shell, Von Blücher-lined overgarment (S3) in the high temperature (100°F), high wind, low humidity environment, their physiological responses were relatively poor. In the 100°F environment, subjects always did significantly worse while wearing S3 relative to both the NYCO/Von Blücher overgarments (P1S,P2S). The PTFE or S3 overgarment had the lowest mean values for all four variables (ET, T_{re}, T_b and %EFF) in that environment. Subjects in the S3 overgarment did better in the lower temperature (86°F), lower wind and higher humidity environment, but still not as well as when they wore either of the NYCO/Von Blücher overgarments. Subjects wearing the BDO had the lowest mean values in that warm, humid environment for all four variables and did significantly worse while wearing either of the NYCO/Von Blücher overgarments for the ET, ΔT_{re} and ΔT_b variables.

As noted in the Introduction, earlier versions of the Von Blücher and PTFE materials were tested in a previous study (Wenger and Santee, 1988). The only material to perform significantly better than the BDO in the 1988 study was a Von Blücher type material (Monopak). The other Von Blücher material (Bipak) did not perform significantly better than the control BDO, but this may be a Type II error due to insufficient subject population size. The earlier PTFE material performed poorly relative to the Monopak and did not represent a significant improvement over the BDO.

There were no significant differences between PTFE S3 and the BDO, and there was an apparent reversal of relative position between the 2 environments. Caution is warranted for the use of data that is not statistically significant, and net water loss (E_{sw}, Table 8) values for PTFE S3 indicate an advantage over BDO, but not over any of the NYCO-shelled garments. Values for sweating efficiency (%EFF) are even less supportive, to the point of indicating that S3 was least efficient in the hot, dry environment. In more humid environments, the overall evaporative potential is reduced, so materials with greater water vapor permeability provide less of an thermoregulatory advantage. Work with the biophysical models has lead to some speculation that PTFE laminates may act as wind barriers. That may partially explain why the S3 overgarment

did worse at 6.5 mph and better at 2.5 mph. Any advantage of greater water vapor permeability is negated by the higher wind speed of 6.5 mph. The basic inference is that, from a thermoregulatory perspective, the PTFE S3 overgarment does not present any significant advantage over the BDO.

The 6.0 oz NYCO shell with 50 mil foam liner (P2F) was not significantly different from the same 6.0 oz NYCO shell combined with a Von Blücher liner (P2S), but the mean value was always lower. P2S was significantly different from BDO and S3; whereas P2F was only significantly different from S3 for ΔT_{re} at 100°F. In addition, P1S was significantly different from P2F in three cases, but P2S was significantly different from P1S in only one special case. The preceding points lead to an inference that P2F was not as good as P2S. Since all other parameters are equal, that would lead to a further inference that the Von Blücher liner had better thermal properties than the 50 mil foam liner.

Data for the 2 NYCO shell overgarments with the Von Blücher liner (P1S with the 4.5 oz NYCO, and P2S with the 6.0 oz NYCO) are very close. They are never significantly different for a full data set. For one case (ET in hot, dry environment) of the data sets without the BDO data, P1S was significantly better than P2S. P1S was significantly better than P2F at 100°F, with the exception of the data for ΔT_{re}. In all cases where there were significant differences between garments, P1S was always better than BDO. In aggregate, the data lead to an inference that P1S is better than P2S. Simple logic and the overall values suggest that the lighter 4.5 oz NYCO shell is better, in terms of thermoregulatory properties. It is, however, equally logical to speculate that the 6.0 oz NYCO shell will be more durable than the lighter 4.5 oz shell.

There is a limited basis for favoring P2F over S3. In the 100°F environment, there was a significant difference for ΔT_{re}. A comparison of mean values also supports a higher ranking for P2F, except for a reversal of ranking for ΔT_b in the warm, humid (86°F) environment.

2. Summary

To summarize the data, the Von Blücher-lined, 4.5 oz NYCO overgarment (P1S) was better than the issue BDO. The Von Blücher-lined, 6.0 NYCO oz overgarment (P2S) was also better than BDO, but there was less statistical support for that conclusion for

hot, dry environments. The 50 mil foam-lined, 6.0 oz NYCO overgarment (P2F) was often significantly worse than P1S, and the mean values for each variable were always below P2S. There was no statistically significant difference between P2S and P2F. There was only a limited statistical basis for superiority of the P2F over the Von Blücher-lined, ECWCS/PTFE overgarment (S3). Finally, there is an insufficient basis for discrimination between the S3 and BDO overgarments. All available data indicates that the S3 overgarment would likely not provide any reduction in physiological strain over the BDO within the tested environments.

B. OTHER CONSIDERATIONS

It should be emphasized that the only basis for comparison between materials presented in this paper are the differences in the physiological responses of the test subjects while wearing the different garments. Consequently, this paper addresses only the thermal properties of the overgarments as they impact thermoregulation. The study demonstrates, under carefully controlled conditions, the relative difference in the thermal strain experienced by the test subjects. Endurance time is presumed to be a demonstration of the impact of thermal strain on the military subjects' abilities to perform a simple physical activity, walking on level ground. The results of this study cannot be directly translated into a prediction of actual tactical performance by military units wearing the test overgarments. We would certainly expect that when there are significant differences under the controlled test conditions, there would be actual differences in the field. However, we can only project relative results. The absolute magnitude of the differences in the field cannot be determined from chamber tests.

This study considered only the effect of overgarments on subjects' thermal states. On that basis, P1S is the best ABDO. If differences in overgarment durability proves to be a significant factor in other testing, it would be difficult to make strong claims regarding the thermal regulatory advantages of P1S versus P2S. Balancing the probabilities of exposure to live agent, a torn or otherwise damaged suit, etc., versus the possible decrement of soldier performance due to thermal strain in a variety of environmental conditions presents a difficult situation. When more elements, such as level of chemical protection, overgarment weight, shelf-life and cost, are included in the decision-making process, it makes it even more difficult to place the value of improved thermal clothing properties in context. Heat casualties will impact troop strength and mission performance, but so may inadequate chemical protection.

V. SUMMARY

It was an objective of the ABDO project to develop an overgarment with improved thermal properties. The results of this study indicate that subjects' physiological responses were best relative to the standard BDO while wearing the P1S (4.5 oz NYCO with Von Blücher lining) and the P2S (6 oz NYCO with Von Blücher lining) overgarment prototypes. From statistical analysis, the inference may be drawn that the PTFE S3 overgarment is not a significantly better overgarment than the BDO.

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